ANALYSIS OF SOIL AND ENVIRONMENTAL PROCESSES ON HYPERSPECTRAL INFRARED SIGNATURES OF LANDMINES

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Abstract— Georgia Tech is in the second year of a Multi-University Research Initiative designed to study the impact of environmental processes on optical signatures. In particular, this program is conducting phenomenological studies on hyperspectral and polarimetric signatures of various target classes in the visible and infrared wavebands. Initial research studies have focused on landmines and the impact of various environmental factors and processes (e.g., subsurface processes) on the resultant spectral infrared signatures. A variety of approaches have been employed in this research to gain a better understanding of the impact of the environment on the spectral and polarimetric characteristics of soil and landmine signatures. These approaches include theoretical analyses, physics-based signature modeling, field measurements, and laboratory studies. We will present results from our research into the use of a physics-based, hyperspectral signature model as an analysis tool for landmine-related phenomenology studies. Results from these studies will be presented that underscore the importance of incorporating the subsurface processes into the signature analyses and the impact of these processes on detection algorithm development. The results of these analyses have been propagated to algorithm developers to permit the creation of more robust processing techniques based on these physical analyses and models.

I. Introduction

The impetus for studying the polarization signatures from soils and landmines, particularly in the long wave infrared (LWIR) arose from the observation that manmade and natural objects exhibit different polarization responses. A significant amount of research in this area has focused on the visible to shortwave infrared region (i.e., 0.4 to 2.5 μm) where these differences have been noted. Additional efforts over the past several years [Sendur, 2001] have begun to examine the potential applicability of polarization in other infrared wavebands, particularly the LWIR. Our work followed up on these assumptions and focused on the LWIR waveband for the specific application of landmine detection.

Our initial research efforts focused on an analytical approach based on multi-layer reflections. This approach rested on the assumed physical model of the target of interest – namely, a painted landmine (metal or plastic) that was covered, at least partially, by a layer of soil (i.e., a 'dirty' landmine). A classical electrodynamics approach was employed to develop the Fresnel reflection equations for a one, two, and three layer scenario. These equations required the complex index of refraction (n - ik) for each layer; thus, any absorption features, etc. could be incorporated into a set of spectral reflection coefficient calculations. Computations were made for a variety of scenarios using these equations under the assumption that the soil layer was quartz sand. Results from these calculations indicated that the sand properties dominated the reflection coefficient down to a soil layer thickness at the sub-micron level.

These initial results were based on an assumption of a continuous medium; in reality the soil layer is composed of particles of various sizes laid down on top of the mine. In addition, the impact of the radiation from the soil itself was not considered in these calculations. Thus, a more rigorous methodology was adopted to provide a more realistic approach to studying this issue. A modeling approach based on the radiative transfer approach outlined originally by Hapke [Hapke, 1993a] was developed and, subsequently extended to include polarization calculations. This radiative transfer approach allows the incorporation of three primary sources of radiation into the computation of radiance observed at the sensor from a subsurface element: (1) radiation reflected directly to the sensor, (2) radiation emitted from the subsurface element, and (3) radiation scattered into the subsurface element and subsequently scattered toward the sensor. The primary source of polarization for the total radiation field remains the emission from the surface toward the sensor but the focus is to incorporate the total radiation field into the calculation. A key feature to this approach is the inclusion of the particle size and shape into the calculations; specifically, this analytical approach models the effect of the scattering and emission of radiation by individual particles into the total radiation field. The particle scattering is modeled through both surface scattering components and internal volume scattering. A critical assumption within the model is that the particle size is much larger than the wavelength; hence diffraction effects are ignored in the calculations. Shape effects are negated by assuming the orientation of the internal surfaces provide enough diversity to allow the

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internal radiation to become unpolarized. The model also accounts for the radiative environment within the subsurface – i.e., the source of the scattered radiation into the subsurface volume.

Calculations were performed with this radiative transfer model to re-examine the LWIR polarization issue. The specific environment selected for these calculations was a soil surface composed of SiO_2 particles. Particle size was chosen consistent with the assumptions embedded in the Hapke theory.

An important assumption in this model is the restriction on the particle size. A hybrid approach that incorporates Mie scattering theory has been proposed and implemented by others for planetary surface environments. We adapted this approach for our calculations to determine the impact of particle size on the polarization metrics. It was anticipated that as the particle size gets closer to the wavelength the wave nature of the radiation will become more important and as a consequence, the polarization metrics would show a dependence on this particle to wavelength ratio. This hybrid model (Hapke-Mie) was implemented for the SiO_2 soil and some initial results obtained.

II. Radiative Transfer Modeling

The equation of radiative transfer (Chandrekashar) expresses the conservation of radiant energy. It provides a framework to calculate how the intensity of an electromagnetic wave changes as it propagates through a complex medium that can absorb, emit, or scatter light.

A. Hapke theory

Hapke's reflectance theory was the first analytic theory to describe the scattering of light from particulate surfaces. Previous theories were either mostly empirical or required extensive computer calculations. Hapke subsequently extended his reflectance theory to include the effects of thermal radiation. In his combined theory of reflectance and emittance spectroscopy, Hapke assumes that the particles in the medium are large compared to the wavelength of light, irregular, and randomly oriented and positioned, and closely packed so that the effects of diffraction can be ignored; this theory is not valid when the particles are uniformly spaced and regular in shape.

Hapke derives the power received by a detector viewing a particulate medium by first calculating the power received from an individual volume element in the surface and then integrating such elements over a semi-infinite half space. Consider an increment of volume dV located at a depth z below the surface a distance r from the detector. Hapke writes the radiance as a sum of three contributions:

$$I = I_1 + I_2 + I_3 \tag{1}$$

where I_1 is the radiation from the source (sun) scattered once by the particles in dV into the direction toward the detector, I_2 is the radiation thermally emitted by the particles in dV toward the detector, and I_3 is the radiation that has been emitted or scattered at least once, impinging on the particles in dV and being scattered toward the detector. The radiance is then expressed as the integral of I over all depths:

$$I = \frac{1}{4\pi}\int_{-\infty}^{0}\left[Jwp(g)e^{\frac{u}{\mu_0}} + 4\gamma^2 B(T) + w\int I(u,\Omega')p(g')d\Omega'\right]e^{\frac{\mu}{\mu_0}}\frac{du}{\mu} \tag{2}$$

where u is a dimensionless distance (u=Ez, where E is the volume extinction coefficient), J is the incident irradiance, w is the single-scattering albedo, p is the average particle angular scattering function, g is the phase angle, $\mu=\cos(e)$ (where e is the angle of observation), $\mu_o=\cos(i)$ (where i is the angle of incidence), $\gamma=\sqrt{(1-w)}$, T is the temperature, and B is the Planck blackbody function.

Hapke assumes that the thermal emission function can be written as a constant term plus an exponentially decreasing term. The first two terms of the radiance equation can be evaluated directly. The last term, the multiply-scattered radiation, is evaluated using the equation of radiative transfer:

Using the two-stream approximation and after a considerable amount of algebra, Hapke derives an expression for the radiance received by the detector:

$$I(i,e,g) = J\frac{w}{4\pi}\frac{\mu_0}{\mu_0+\mu}\left[p(g) + \left(H(w,\mu_0)H(w,\mu)-1\right)\right] + \left[\frac{B_0}{\pi}\gamma H(w,\mu) + \frac{B_1}{\pi}\frac{L}{L+\mu}\gamma^2 H(w,L)H(w,\mu)\right] \tag{3}$$

where L is the dimensionless emission scale height, B_0 is the constant term in the emission function, B_1 is the coefficient of the exponential in the emission function, and H is the Chandrasekhar H-function. The first term on the right hand side of Equation (3) describes the reflected component of the radiation received by the detector and the second term describes the thermally emitted radiance. This equation, along with the equation for single scattering albedo forms the basis for the extension of the Hapke model for polarization and particulate size.

The single scattering albedo, w, is defined in terms of the particle scattering efficiency and total extinction efficiency. In the geometric approximation two processes govern the scattering by a particle: external (reflection from the surface of the grain) and internal (volume scattering of rays from the interior of the particle). Hapke uses a slab model to approximate the scattering from a large, equant particle and calculates the scattering efficiency, Q_S, in terms of the external scattering coefficient and the internal scattering coefficient. Hapke makes a two-stream approximation and obtains an expression for the scattering efficiency of an irregularly shaped grain with a fixed diameter. This expression incorporates both the particle size and volume scattering effects.

B. Extension to Polarization

As summarized above, the Hapke model does not explicitly include polarization. Hapke argued that this assumption could be partially justified because large, irregular, dielectric particles do not polarize light strongly by scattering. A soil surface will be composed of particles of various sizes – including those with average diameters that violate the original assumptions in the Hapke model. If we relax the large particle assumption we can expect polarization effects to arise.

First, we consider the thermally emitted component received at the detector. First-order polarization effects may be included if we assume that the radiation that has been emitted or scattered at least once impinging on the particles in dV is unpolarized and only becomes polarized under scattering toward detector. Since we assume that the particles are randomly oriented then the planes of scattering between the particles have been randomly rotated and to a first approximation this assumption is justified. The two components of the scattered radiance are therefore:

$$I_{\perp}^{(T)}(i,e,g)=\frac{1}{4\pi}\int_{-\infty}^{0}\left[4\gamma_{\perp}^{2}B(T)+\int\left[wp(g')\right]_{\perp}I(u,\Omega')d\Omega'\right]e^{u/\mu}\frac{du}{\mu}$$
$$I_{\parallel}^{(T)}(i,e,g)=\frac{1}{4\pi}\int_{-\infty}^{0}\left[4\gamma_{\parallel}^{2}B(T)+\int\left[wp(g')\right]_{\parallel}I(u,\Omega')d\Omega'\right]e^{u/\mu}\frac{du}{\mu} \tag{4}$$

where $\perp(\parallel)$ indicate the portion of the radiance perpendicular (parallel) to the scattering plane. Using the equation of radiative transfer and the two-stream approximation one obtains the Hapke equation for each component of the scattered intensity:

$$I_{\perp}^{(T)}(i,e)=\left[\frac{B_0}{\pi}\gamma_{\perp}H(w_{\perp},\mu)+\frac{B_1}{\pi}\frac{L}{L+\mu}\gamma_{\perp}^{2}H(w_{\perp},L)H(w_{\perp},\mu)\right]$$
$$I_{\parallel}^{(T)}(i,e)=\left[\frac{B_0}{\pi}\gamma_{\parallel}H(w_{\parallel},\mu)+\frac{B_1}{\pi}\frac{L}{L+\mu}\gamma_{\parallel}^{2}H(w_{\parallel},L)H(w_{\parallel},\mu)\right] \tag{5}$$

Similarly, first-order polarization effects may be included in the reflected component of the radiation in Equation (3) if we assume that the multiply-scattered radiance has no net polarization and the incident radiance is unpolarized [Hapke, 1993b]. This gives:

$$I_{\perp}^{(R)}(i,e,g)=\frac{J}{2}\frac{1}{4\pi}\frac{\mu_0}{\mu_0+\mu}\left\{\left[wp(g)\right]_{\perp}+\left(H(w,\mu_0)H(w,\mu)-1\right)\right\}$$
$$I_{\parallel}^{(R)}(i,e,g)=\frac{J}{2}\frac{1}{4\pi}\frac{\mu_0}{\mu_0+\mu}\left\{\left[wp(g)\right]_{\parallel}+\left(H(w,\mu_0)H(w,\mu)-1\right)\right\} \tag{6}$$

There are two sources of scattering from an individual particle: 1) external Fresnel reflection from the surface and 2) refraction or scatter from the interior. For an irregular particle the orientation of the scattering plane of the light refracted or scattered from the interior is randomized. Therefore we can assume that the volume-scattered light is unpolarized. Under these assumptions we can derive a simple expression for the first terms in each bracket based on the Fresnel coefficients.

C. Hapke/Mie hybrid with polarization

We now extend the above polarization model to include effects that are expected to be important when the wavelength of light and the particle size are similar. This is accomplished with the Hapke/Mie hybrid theory of Moersch and Christensen [Moersch and Christensen, 1995] in which the Mie-derived single-scattering albedo, corrected for close-packing [Wald, 1994], is used in Hapke's multiple scattering theory. The close-packing correction is Wald's "diffraction subtraction" and is given by:

$$w_{hybrid}=2w_{Mie}-1 \tag{7}$$

It is introduced to accommodate the overlap of the diffraction disks in a real surface when particles are touching. Moersch and Christensen considered a number of scattering models and compared the predictions of each model with measured spectra. They found that this hybrid theory provides the best fit of the observed emissivity measurements of quartz. Therefore, following Moersch and Christensen we consider a Hapke/Mie hybrid theory and use a Mie-derived single-scattering albedo, corrected for close-packing with Wald's subtraction, in the Hapke equation for each component of the intensity in order to examine particle size effects.

III. Results

A. Polarization Calculations

It is straightforward to apply the polarization model outlined above to the soil-landmine system. In this section we present the results of our numerical modeling for the flush-buried mine (~1" of overlaying soil) in the LWIR (8 – 12 μm). We assume that the soil is composed of amorphous quartz. The real part and the imaginary part of the index of refraction (N=n-ik) of amorphous quartz are given in Popova et al. [Popova, et al, 1972]. The atmosphere is treated as a blackbody source with an effective temperature depending on the time of day. The boundary conditions for the thermal emission function were derived from the temperature profile calculated by the Georgia Tech high spatial resolution digital thermal model of the soil-landmine system [Campbell, et al, 2004]. This model uses the Georgia Tech Signature (GTSIG) software to predict the temperature and radiance of the soil-landmine system as a function of the operating state and environmental parameters.

The numerical modeling of Hapke's theory was performed in MATLAB. The only free parameter in Hapke's emission theory is sD - the internal volume-scattering coefficient times the particle diameter. Moersch and Christensen, who modeled the emissivity of quartz in the thermal band, found that the spectra resulting from Hapke's model are insensitive to the choice of this parameter. Following Moersch and Christensen we fixed this parameter at a value of 0.3.

The Degree of Linear Polarization (DOLP) is defined as:

$$DOLP = \frac{I_{\perp} - I_{\parallel}}{I_{\perp} + I_{\parallel}} \tag{8}$$

where (see Equations 5 and 6):

$$\begin{aligned} I_{\perp} &= I_{\perp}^{(T)} + I_{\perp}^{(R)} \\ I_{\parallel} &= I_{\parallel}^{(T)} + I_{\parallel}^{(R)} \end{aligned} \tag{9}$$

In Figure 1 we show the DOLP vs. observation angle for several wavelengths in the LWIR for a flush-buried mine at 11:00 am (T_{atm}=298.5 K). The calculation was performed using Hapke's theory with the average SiO_2 particle size taken to be 100 µm, much greater than the LWIR wavelengths in accordance with Hapke's general assumptions. These results indicate pronounced changes in DOLP (both magnitude and sign) as the wavelength increases.

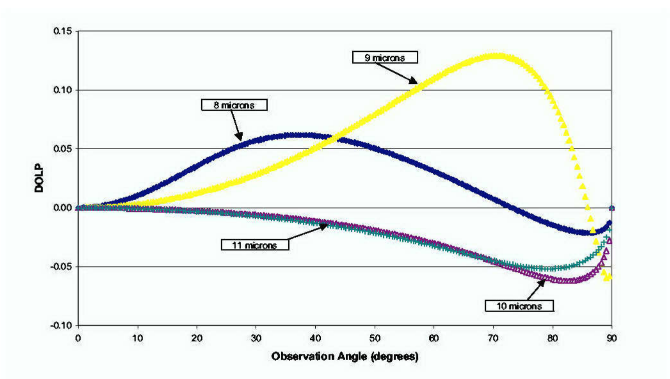

Figure 1. DOLP vs. Observation Angle at discrete LWIR wavelengths.

B. Particle Size Effects

Placement of a landmine below the surface will necessarily disturb the soil. The burying process – soil displacement followed by soil replacement over the landmine – will introduce fine particles directly above the burial site. Therefore, it is important to examine how the polarization characteristics of the soil vary with changes in particle size.

Again, we consider the flush-buried case under the same conditions as above and calculate the effects of changing the particle size. For particles much larger than the wavelength of light we use Hapke's theory to calculate the DOLP. When the average particle size and the wavelength of light are similar, we use the Hapke/Mie hybrid theory, corrected for close-packing, as described above. The Mie single-scattering algorithm used here was derived from a code written by C. Matzler [Matzler, 2002]. Radiance and DOLP calculations were made for 9 µm radiation of Hapke theory with an average particle size of 100 µm with the Hapke/Mie hybrid theory with an average particle size of 10 µm. At this wavelength we saw no significant difference between the two DOLP curves.

In Figure 2 we show a comparison at 11 µm radiation of Hapke theory for average particle sizes of 70 and 100 µm and for the Hapke/Mie hybrid theory with average particle sizes of 10 and 40 µm. At 11 µm we see a particle-size dependence in the DOLP. We found that the term in Hapke's radiance equation that is linear in Chandrasekhar's H-function is the dominant contribution to the polarization curves (this is partly to be expected from the fundamental assumptions of the polarization model outlined above). The H-function is a function of the single-scattering albedo; it is this dependence that leads to the variation observed in Figure 2.

These preliminary results indicated that a change in the DOLP is indeed based on the particle size –both the magnitude as well as the size of the metric. Additional studies are required to fully explore and understand these results but the preliminary work is promising, especially in the context of the disturbed soil problem. For example, as disturbed soil weathers one expects the particle size distribution to change. If these polarization results hold, it may provide a means to determine the predominant particle size and hence determine the 'exposure time' for the disturbed soil.

C. Summary

Hapke's theory is only an approximate theory and therefore a more robust theory is required. Furthermore, field data is crucial to verify the model results outlined above. However, the results obtained from this study suggest that the DOLP predicted by a multiple-scattering, particulate theory provides a means to characterize the soil disturbance around landmines; particularly in regard to ageing and weathering.

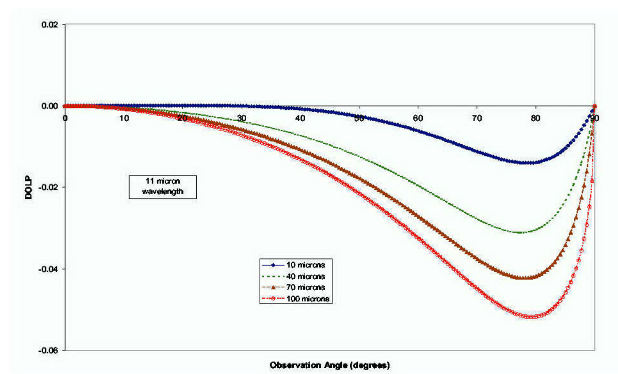

Figure 2. DOLP Calculations for varying particle sizes.

IV. LANDMINE MODELING

Detailed studies of the environmental impact on the electro-optical signatures of soil and landmines require the development of digital models. The complex, time-varying, spatial dependent processes that are part of a typical soil defy analytical solution except under the most restrictive of assumptions (leading to unrealistic scenarios). Thus one of the earliest research efforts under this MURI focused on developing a digital model of the landmine-soil system to aid in these phenomenology analyses. A major requirement of this model was that it incorporates sufficient spatial detail and includes the relevant physical processes to enable the conduct of the aforementioned analyses. This initial model was constructed using the technical approach embodied within the Georgia Tech infrared signature code, GTSIG. The major adaptation made during the model development was the fine-scale spatial resolution network necessary to represent the landmine-soil system. Within the framework of the GTSIG approach, an M19 landmine was modeled for three different deployment scenarios (surface, flush-buried, buried) – a spatial resolution of 5.5 x 5.5 x 5.5 cm^3 was used within the model to define both the geometry and heat transfer components. Details on the model construction can be found in [Campbell, et al, 2004] but, basically, the modeling environment allows specification of soil properties at the scale of the spatial resolution and controls the energy flow into and out of the system through specification of the external and internal energy sources. Thus, mechanisms such as solar heating, wind convection, sky-to-earth radiative transfer, heat conduction, etc. are components included in the numerical solution of the heat transport equation. Much of the environmental data is captured in a single meteorological data file to allow utilization of the model in different geographic scenarios.

The initial model assumed a soil composed entirely of SiO_2 throughout all of the layers. This model provided a means to verify several modeling assumptions and to conduct preliminary phenomenology studies. For the next sequence of such studies a revised landmine-soil model was required. A more realistic model was developed based on soil horizon data obtained from a United States Department of Agriculture (USDA) soil information database. This new model restructured the subsurface to conform to the approximate size and composition of each subsurface horizon. Relative contributions of clay, sand, and silt were defined for each soil layer; relevant physical properties (e.g., density, heat capacity, etc.) were computed based on a fractional contribution of the individual constituents to the total soil layer volume.

Analyses with this revised model involved several areas of interest. First, a series of computations to verify the operation of the model were conducted. These calculations indicated the thermal connections and environmental inputs were being handled appropriately within the model. Figure 3 shows an example of a temperature profile computed by the model and compared against field data obtained from the USDA. These data were computed using a multi-day meteorological data file; temperature data were extracted for the 30th day and used for comparison. As can be seen the model results are consistent with the field data. Differences between the two arise from multiple sources including incomplete specification of the soil optical properties and assumptions made on the solar radiation inputs. These soil optical properties are a major factor in the coupling of energy into and out of the soil. In addition, the model results are also consistent with results from other researchers. Second, the model was used for comparison to data collected during field exercises; specifically, data collected by the University of Hawaii AHI sensor for a government collection program. This task involved a more detailed spectral comparison between the model results and field data. The results of this comparison were promising and indicated the model was consistent with the data [Cathcart, et al, 2004]. Third, an analysis of the relative impact of various environmental and physical factors on the temperature predictions was initiated. This study served to identify those factors that produced the most significant influence on the thermal signatures of the landmine-soil system. The initial phase of this study focused on the soil factors alone. The data from this study convincingly illustrates the point that knowledge of key aspects of the environment is crucial to accurately modeling and studying electro-optical signatures. Companion studies to the one described indicate a need to understand the soil optical properties in detail.

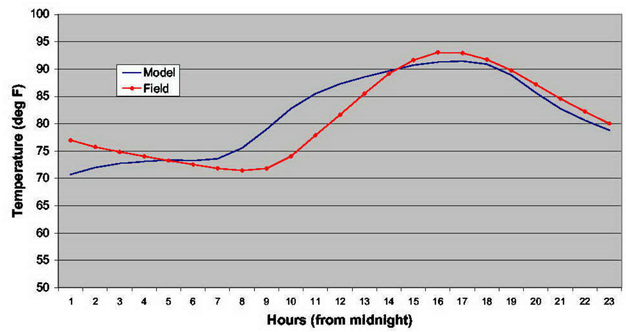

Figure 3. Soil Temperature Comparison at 2" depth for Arizona test site

V. SPECTROSCOPIC STUDIES

In a previous paper [Cathcart, et al, 2003], the initial results of the spectroscopic measurement program were reviewed. Those measurements were made on a sample of SiO_2 particles containing various grain sizes (average grain size of ~ .06 mm), i.e., our simple soil model. That study focused on examining the impact of water on the spectral structure of SiO_2 during a dry-wet-dry cycle. Results from those measurements clearly indicated a change in the spectra of the quartz particles under this cycling with water; specifically the spectral feature near 9.5 microns showed a significant shift in wavelength and broadening due to the presence of the water molecules. The line width showed an increase of ~50% and an amplitude increased by a factor of 8 for the saturated state. It was further shown that mechanically disturbing the dried sample resulted in those features reverting back to their initial values. These results were significant as this spectral feature falls within the restrahlen band of quartz; a feature of interest to the landmine community.

These results illustrate a need to conduct additional spectral studies to quantify the observed changes, characterize the environmental aspects in more detail, and examine the impact of additional environmental factors. These new studies focused on the following areas: temperature effects, grain studies, and polarization measurements. A review of the literature was also conducted to aid in understanding these results and in establishing hypotheses for the observed effects. An Attenuated Total Reflectance (ATR) spectrometer, resident in the School of Chemistry, was used to make these spectroscopic measurements; the spectral region spanned by this device covers the infrared region from 1 to 25 microns. An additional component was designed and added to this apparatus – an environment chamber to allow temperature and humidity control for the sample under observation. This chamber was employed to determine both the impact of temperature and wet-dry cycling on the spectral properties.

After construction and installation of the chamber, temperature studies were conducted on several quartz particle samples. The results from these temperature studies showed no measurable impact on the spectral features over the range of temperatures tested. As a consequence, further temperature related studies were put on hold.

Additional studies were performed related to the impact of water on the spectral properties; the environment chamber was utilized for these measurements also as the moisture conditions can be accurately controlled and monitored. These measurements continued to examine the impact of the dry-wet-dry cycle that was part of the first study. A component of those studies examined the impact of the grain size distribution on the observed spectra. Figure 4 illustrates an example of these measurements for a fine grain particle size (~10 μm^2). From a comparison with similar data for a coarse grain sample (~1 mm^2) a spectral shift was seen between the two size distributions. The changes in the spectral features were qualitatively consistent with measurements taken in the field. With those observations it is speculated that the water, during the wetting cycle, acts to compact the quartz particles, producing a denser medium which leads to stronger absorbance. In addition, the heterogeneous mixture of grain sizes contributes to this process – when water is present in sufficient quantity it is hypothesized that the fine grains are forced into the interstitial spaces which in turn substantially increases the effective grain area for absorbance. One focus of future research in this area will be to quantitatively address the grain size issue through measurements on mono-dispersed size distributions. These measurements will provide a means for isolating the effects of grain size on the spectral changes of SiO_2.

Questions surrounding the utility of polarimetric signatures coupled with the birefringent nature of quartz led to a series of ATR measurements using a polarized light source. These measurements revealed a polarimetric dependence to the response of the SiO_2. Figure 5 shows an example spectra taken of a sample for two linearly polarized light sources. For comparison a corresponding spectra from an unpolarized light source is also shown. A pronounced splitting of the absorption feature at 9.2 μm is evident in this figure; a literature review suggests that it is related to the Berreman effect first observed for thin films of SiO_2. This effect involves the splitting of the transverse optical and longitudinal optical modes of the asymmetric stretch mode for SiO_2. Based on this result it seems likely that a polarized effect might be observable in the field; such a measurement might have utility within the detection problem. Whatever the explanation for the splitting it leads to the need for further polarization measurements (particularly field measurements) to confirm these initial results and to determine the utility of the feature for soil measurements. The University of Hawaii can aid in the field measurements through the use of their Airborne Hyperspectral Imager; this instrument covers the LWIR band and has recently been outfitted with a polarization capability.

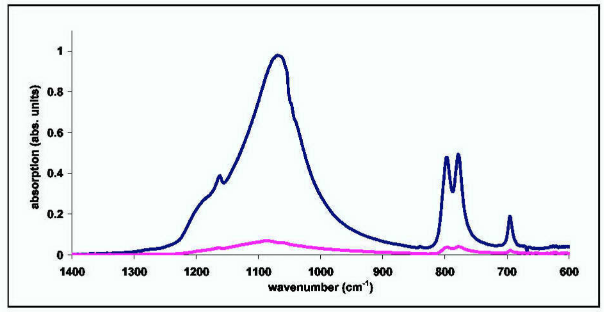

Figure 4. ATR Spectrum for fine grain size – pristine case (bottom curve); after wetting with water and drying (top curve)

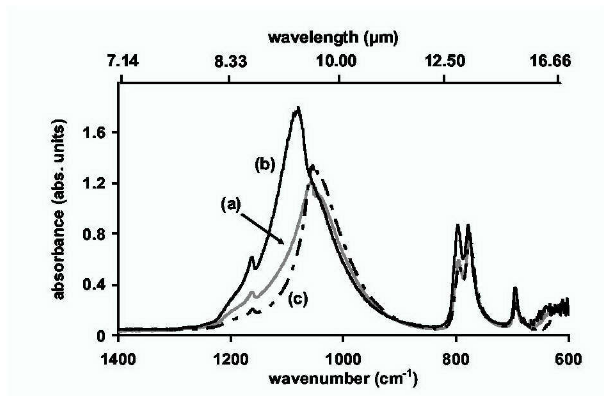

Figure 5. SiO_2 spectra using polarized light (a) unpolarized light (b) p-polarization (c) s-polarization

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